WEED MANAGEMENT

Weed Management Systems for Conventional and Glyphosate-Resistant Soybean with and without Irrigation

Larry G. Heatherly,* C. Dennis Elmore, and Stan R. Spurlock

ABSTRACT

Management inputs that maximize economic return from the early soybean [*Glycine max* (L.) Merr.] production system have not been evaluated fully. The objective was to determine the effect of weed management on yield and net return from early planted maturity group (MG) IV and MG V glyphosate [*N*-(phosphonomethyl)-glycine]-resistant (GR) and conventional (CONV) soybean cultivars grown in the early soybean production system with (IRR) and without (NI) irrigation. Field studies were conducted from 1996 through 1999 on Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquert) at Stoneville, MS (33°26′ N lat). Weed management systems were (i) pre-emergent (PRE) broadleaf followed by postemergent (POST) broadleaf and grass weed management (PRE + POST) and (ii) POST broadleaf and grass weed management (POST). Use of POST-only weed management was cheaper, yielded more, and resulted in greater net returns than did use of PRE + POST weed management with both CONV and GR cultivars. Under the conditions of this study, use of GR vs. CONV cultivars in an NI or low-yield environment resulted in greater profit ($52 vs. −$17 ha^{-1} 3-yr average, respectively). Use of CONV vs. GR cultivars resulted in greater profit in an IRR or high yield environment ($382 vs. $266 ha^{-1} 3-yr average, respectively). These results indicate that use of GR cultivars with POST-only weed management will result in greater profit in an NI environment while use of CONV cultivars with POST-only weed management will result in greater profit in an IRR environment.

Soybean, especially when not irrigated, provides relatively low gross return with a small margin for profit in the midsouthern USA (Heatherly and Spurlock, 1999; Williams 1999). This small profit margin dictates that all inputs associated with production must be evaluated with respect to their likelihood of increasing profitability and that yield losses due to controllable pests such as weeds must be prevented within economic constraints. The objective of the producer is to control weeds adequately to maximize profits; however, inputs used for weed management in soybean represent a significant cost (Heatherly et al., 1994; Buhler et al., 1997; Johnson et al., 1997; Reddy and Whiting, 2000). In narrow-row soybean plantings made in a stale seedbed (a seedbed that has not been tilled since the preceding fall; Heatherly, 1999b), weed management programs involve herbicides almost exclusively (Oliver et al., 1993; Johnson et al., 1997, 1998). Weed management expenditures are almost always made before the onset of drought and without knowledge of ensuing moisture status for subsequent crop and weed development. This presents a challenge, especially in NI production systems that often result in low yield in the midsouthern USA.

A majority of the soybean hectarage in the midsouthern USA is NI even though past research has shown that yield and net return will increase from irrigation (Heatherly, 1999a). The small profit margin and large start-up costs associated with land leveling to accommodate furrow or flood irrigation, or the initial purchase cost associated with overhead irrigation systems, can make capitalization of irrigation capability prohibitive. Thus, most land used for soybean production in the midsouthern USA presently is committed to either an IRR (start-up costs absorbed in past) or NI production system. Management of NI and IRR plantings of soybean in the midsouthern USA entails different sets of production practices, especially for weed management (Heatherly et al., 2002), because the opportunity for profit is different between the two systems (Heatherly and Spurlock, 1999).

Many weed management systems (WMSs) provide similar control levels, but cost differences can be large. Cost differences, coupled with yield differences, can mean significant differences in net return among WMSs (Poston et al., 1992; Heatherly et al., 1993, 1994; Buhler et al., 1997; Johnson et al., 1997; Nelson and Renner, 1999; Webster et al., 1999; Reddy and Whiting, 2000; Reddy, 2001a). Thus, effective weed management programs that are economical for a given production system must be determined to maximize profits.

Traditionally, herbicides were tailored largely for crops rather than crops tailored to tolerate a specific herbicide. During the past decade, advances in biotechnology, coupled with plant breeding, have resulted in the development of herbicide-resistant soybean cultivars. As of 2000, GR soybean represents all of the hectarage planted to transgenic soybean (Reddy, 2001b). Well over half of the U.S. soybean area is planted to GR soybean cultivars, with some states having more than two-thirds of their soybean area in GR soybean. Reddy et al. (1999) and Reddy (2001b) recently summarized the current situation pertaining to the use of GR soybean cultivars. Glyphosate has low mammalian toxicity and is considered environmentally safe. Glyphosate is a nonselective herbicide that kills both annual and

L.G. Heatherly, USDA-ARS, Crop Genet. and Prod. Res. Unit, P.O. Box 343, Stoneville, MS 38776; C.D. Elmore, USDA-ARS, Appl. and Prod. Technol. Res. Unit, P.O. Box 36, Stoneville, MS 38776; and S.R. Spurlock, Dep. of Agric. Econ., P.O. Box 9755, Mississippi State, MS 39762. Received 25 Feb. 2002. *Corresponding author (lheatherly@ars.usda.gov).

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Abbreviations: CONV, conventional; GR, glyphosate resistant; IRR, irrigated; MG, maturity group; NI, nonirrigated; POST, postemergent; PRE, pre-emergent; WMS, weed management system.

perennial grass and broadleaf weeds with one application. There is no sequence-of-application concern as there is with herbicides that kill either grass weeds or broadleaf weeds but not both. Controlling weeds of the same species that differ in size can be attained simply by increasing glyphosate rate. Thus, herbicide application timing for adequate weed control is of less concern than when using nonglyphosate herbicides. Because glyphosate does not carry over to subsequently planted crops or persist in an active form in the soil, producers can use a glyphosate-only weed management program with no concern for choice of rotational or following crops. Taylor et al. (1999) demonstrated that composition of seed from soybean that was treated with glyphosate is equivalent to that from plants not treated with glyphosate. Padgette et al. (1996) concluded that, except for tolerance to glyphosate, GR genotypes are substantially equivalent to parental and other soybean cultivars.

Glyphosate-resistant cultivars offer producers the flexibility to control a broad spectrum of weeds in soybean without crop safety concerns (Reddy, 2001b). Weed control cost is less, even when the higher cost for seed of most GR cultivars is considered (Reddy et al., 1999; Roberts et al., 1999; Webster et al., 1999; Reddy and Whiting, 2000; Reddy, 2001a). This translates to increased profits if yields from GR cultivars are equal or nearly equal to those from CONV cultivars (Reddy and Whiting, 2000). However, if yields of GR cultivars are greatly below those of CONV cultivars, the cost advantage for a weed management program with glyphosate will not result in greater net returns (Webster et al., 1999).

Research has shown that nonglyphosate PRE herbicides do not adversely affect GR soybean (Gonzini et al., 1999; Nelson and Renner, 1999; Webster et al., 1999; Reddy, 2001a). This means that residual herbicides can be used on plantings of GR cultivars to prevent early-season weed competition in situations where a timely application of glyphosate is not possible (Corrigan and Harvey, 2000). Glyphosate applied at labeled use rates does not affect GR soybean adversely (Nelson and Renner, 1999; Reddy et al., 2000; Elmore et al., 2001a). Glyphosate applied alone in a timely manner to GR soybean plantings needs no supplementation with nonglyphosate herbicides to achieve maximum weed control and yield (Gonzini et al., 1999; Webster et al., 1999; Corrigan and Harvey, 2000; Reddy and Whiting, 2000; Reddy, 2001a). All of these advantages should translate to a reduction in management decisions for producers related to weed control in soybean when GR cultivars are used.

Comparisons in side-by-side cultivar performance trials suggest that GR cultivars may yield less than CONV soybean. Differences in yield between GR and CONV cultivars may result from either cultivar genetic differentials or the GR gene or gene insertion process. In a Nebraska study (Elmore et al., 2001b), five backcross-derived pairs of GR and CONV soybean sister lines were compared along with three high-yielding CONV cultivars and five other herbicide-resistant cultivars in an IRR environment. Glyphosate-resistant sister lines yielded 5% (200 kg ha^{-1}) less than the CONV sister lines. High-yielding CONV cultivars included for comparison yielded 5% more than the non-GR sister lines and 10% more than the GR sister lines. Producers should consider the potential yield advantage of CONV cultivars as they evaluate profit opportunity of CONV and GR systems. This is especially true in high-yield environments such as with irrigation in the midsouthern USA. However, if weeds that are difficult to control with nonglyphosate herbicides are present, the GR system still may be the most profitable, especially in low-yield environments where costs must be minimized. Any yield difference between GR and CONV cultivars should be assessed economically because use of GR cultivars and glyphosate results in lower weed management costs (Roberts et al., 1999; Webster et al., 1999).

The objective of this research was to compare the yield and economic return from GR and CONV soybean cultivars grown with PRE + POST or POST-only weed management strategies designed to provide acceptable weed control in NI and IRR environments in the midsouthern USA. Economic analysis of 4 yr of results was conducted to assess the profitability of the two WMSs on clay soil. Seed yields and estimated costs and returns were used to generate budgets for the economic comparisons.

MATERIALS AND METHODS

Field studies were conducted from 1996 through 1999 at the Delta Research and Extension Center at Stoneville, MS (33°26′ N lat), on Sharkey clay (very-fine, smectitic, thermic chromic Epiaquert). Separate NI and IRR experiments were conducted using a randomized complete block design with four replicates of all treatments each year. Treatments were arrayed in a split-plot factorial arrangement, with cultivar (MG IV and V CONV and GR) as the main plot and WMS as the subplot. Treatments were assigned randomly to plots at the beginning of the study period and remained in the same location thereafter to determine effects where the same weed management was used continuously over a period of years.

Planting dates, cultivars used each year, and seed costs (including technology fee for GR cultivars) are shown in Table 1. The intent was to use the early soybean production system (Heatherly, 1999a) for all plantings, but wet soil in April and early May 1999 prevented early planting that year. Cultivars were chosen based on regional variety trial results, use patterns by producers, and recency of release. Cultivars were updated throughout the study period to ensure that recently released, relevant cultivars that offered potentially improved performance were used. Seed were treated with metalaxyl [*N*-(2,6-dimethylphenyl)-*N*-(methoxyacetyl)-DL-alanine methyl ester] fungicide at 0.3 g a.i. kg^{-1} seed before seeding in 1996 and with mefenoxam [*N*-(2,6-dimethylphenyl)-*N*-(methoxyacetyl)-D-alanine methyl ester] fungicide at 0.11 g a.i. kg^{-1} seed before seeding in succeeding years.

Row width was 0.5 m, and seeding rate was 16 seed m^{-1} row, or about 50 kg ha^{-1} seed. Plots were 4 m wide (eight rows) and 30.5 m (IRR) or 22.9 m (NI) long. The eight-row-wide plots were composed of four rows between and two rows outside of two furrows created by the tractor (2-m wheel spacing) during planting. All experiments were seeded into a stale (untilled) seedbed (Heatherly and Elmore, 1983; Heatherly et al., 1993; Heatherly, 1999b) that had been tilled the preceding fall. Shallow tillage (≤10 cm) in the fall of 1995 and 1996 was done using a disk harrow and spring-tooth field

Table 1. Planting date, maturity group (MG), cultivar type [conventional (CONV) and glyphosate resistant (GR)], and seed cost ($ kg^{-1}) of soybean cultivars grown in nonirrigated and irrigated plantings at Stoneville, MS, 1996–1999.

Year	Planting date	Cultivar (MG†)	Cultivar type	Seed cost‡
				$ kg^{-1}
1996	26 Apr.	Delta & Pine Land Co. DP 3478 (IV)	CONV	0.66
		Monsanto Co. Asgrow AG 4701 (IV)	GR	0.88
1997	14 Apr.	Cache River Valley Dixie 478 (IV)	CONV	0.65
		Hutcheson (V)		0.42
		Monsanto Co. Hartz H 4998 (IV)	GR	1.14
		Monsanto Co. Hartz H 5545 (V)		1.14
1998	2 Apr.	Cache River Valley Dixie 478 (IV)	CONV	0.74
		Pioneer Hi-Bred Int. P 9511 (V)		0.74
		Monsanto Co. Hartz H 4994 (IV)	GR	1.18
		Delta & Pine Land Co. DP 5806 (V)		1.18
1999	17 May	Garst Seed Co. AgriPro AP 4880 (IV)	CONV	0.75
		Pioneer Hi-Bred Int. P 9594 (V)		0.75
		Pioneer Hi-Bred Int. P 9492 (IV)	GR	1.22
		Delta & Pine Land Co. DP 5644 (V)		1.22

† MG assigned by originator of cultivar and may not be relative to other cultivars in study.
‡ Includes technology fee for GR cultivars.

cultivator. In the fall of 1997, the NI site was deep-tilled to a 45-cm depth with a chisel plow having shanks spaced 1 m apart while the IRR site received the same shallow tillage as in previous years. In the fall of 1998, both sites were deep-tilled. All deep-tillage operations were followed by disk and spring-tooth harrowing to smooth the seedbed for the following spring's planting. Glyphosate at 840 g a.i. ha^{-1} in 94 L ha^{-1} water was applied preplant to each experimental site each year to kill existing weed vegetation.

Weed management systems included only herbicides and were selected using two premises: (i) Because the intent in this study was to use proven weed management options that differ in cost, PRE weed management (based on expected weed infestations) followed by POST weed management (based on actual weed infestations) was compared with POST-only weed management, and (ii) use of GR cultivars offers opportunity for using the broad-spectrum glyphosate in a POST-only management system. However, use of PRE herbicides with these cultivars is often touted as a way of ensuring effective early-season weed control without sole dependence on the timely application of POST glyphosate. Based on these premises, WMSs each year were (i) PRE broadleaf followed by POST broadleaf and grass weed management (PRE + POST) and (ii) POST broadleaf and grass weed management (POST). Within each WMS, use of herbicides (not necessarily the same ones each year) and their combinations was dictated by expected weed populations (PRE) or actual populations (POST). Expert opinion during the growing season was used to determine when weed population within each WMS was sufficient to justify application of POST herbicides and what herbicides to use. The POST weed management inputs were applied only when determined to be necessary based on weed presence. Two applications of glyphosate applied sequentially to GR cultivars in the POST treatment are supported by results from previous research (Gonzini et al., 1999; Wait et al., 1999; Payne and Oliver, 2000; Swanton et al., 2000). The objective was to use the herbicides most likely to minimize weed competition within the constraints of each individual WMS each year.

Herbicides were broadcast-applied each year at labeled rates with recommended adjuvants and in recommended tank mixes (Table 2). Pre-emergent herbicides were applied immediately after planting each year. In all years, $\geq$13 mm of rainfall occurred within 10 d of each PRE application. Pre-emergent herbicides and POST broadleaf herbicides were applied in 187 L ha^{-1} water, whereas POST grass herbicides and glyphosate were applied in 94 L ha^{-1} water. Herbicides were applied using a canopied sprayer (Ginn et al., 1998a) for over-the-top applications (to prevent drift to adjacent plots of different treatments) or a directed sprayer (Ginn et al., 1998b) for applications underneath the developing soybean canopy. Application rates for each herbicide were metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one] at 450 g a.i. ha^{-1} applied PRE, imazaquin {($\pm$)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-quinolinecarboxylic acid} at 137 g a.i. ha^{-1} applied PRE, premix of metribuzin at 450 g a.i. ha^{-1} in 1996–1998 and 360 g a.i. ha^{-1} in 1999 plus chlorimuron {2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoic acid} at 75 g a.i. ha^{-1} in 1996–1998 and 60 g a.i. in 1999 applied PRE, premix of bentazon [3-isopropyl-1*H*-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide] at 560 g a.i. ha^{-1} plus acifluorfen {5-[2-chloro-4-trifluoromethyl)phenoxy]-2-nitrobenzoid acid} at 280 g a.i. ha^{-1} applied POST, sethoxydim {2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one} at 213 g a.i. ha^{-1} applied POST, a tank mix of 2,4-DB [4-(2,4-dichlorophenoxy)butanoic acid] at 224 g a.i. ha^{-1} plus linuron [*N*-(3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea] at 560 g a.i. ha^{-1} applied POST as a directed spray underneath the soybean canopy, and glyphosate applied POST at 840 g a.i. ha^{-1}.

In the IRR experiments, water was applied by the furrow method through gated pipe whenever soil water potential at the 30-cm depth, as measured by tensiometers, decreased to -70 kPa. The effect of irrigation on yield of soybean in the midsouthern USA is well documented (Heatherly, 1999c), but irrigation environment can also affect infestation levels of some weed species (Heatherly et al., 1994, 2001, 2002). Amounts of irrigation water applied and irrigation starting and ending dates each year were 267 mm (all cultivars) applied between 18 June and 25 July in 1996, 200 mm (MG IV CONV cultivar) and 300 mm (all other cultivars) applied between 7 July and 19 August in 1997, 360 mm (MG IV CONV cultivar) and 500 mm (all other cultivars) applied between 17 June and 25 August in 1998, and 360 mm (MG IV cultivars) and 400 mm (MG V cultivars) applied between 7 July and 31 August in 1999. Applied water traversed the area in furrows created during seeding by the tractor wheels that were spaced 2 m apart. Irrigation amounts were determined by the degree of cracking in this shrink-swell soil (cracks when dry, swells when wet) because water applied to it through surface irrigation flows downward to the depth of cracking and rises to the surface as the cracks fill (Mitchell and van Genuchten, 1993). Weather data presented in Table 3 were collected approximately 0.8 km from the experimental site by Delta Research and Extension Center personnel.

Weed cover was determined (Elmore and Heatherly, 1988)

Table 2. Pre-emergent (PRE) and postemergent (POST) herbicides applied to nonirrigated (NI) and irrigated (IRR) plantings of conventional (CONV) and glyphosate-resistant (GR) soybean at Stoneville, MS, 1996–1999. Indicated herbicides applied to both NI and IRR unless otherwise noted.

WMS†	Cultivar	Herbicide and no. of days after planting applied‡
		1996
PRE + POST	CONV	PRE: metribuzin. POST: bentazon + acifluorfen (27); sethoxydim (35); bentazon + acifluorfen (41).
POST	CONV	POST: bentazon + acifluorfen (21); sethoxydim (35); bentazon + acifluorfen (41).
PRE + POST	GR	PRE: metribuzin. POST: glyphosate (27); glyphosate (41).
POST	GR	POST: glyphosate (21); glyphosate (41).
		1997
PRE + POST	CONV	PRE: metribuzin + chlorimuron. POST: sethoxydim (1/2§; 53); bentazon + acifluorfen (NI; 56); 2,4-DB + linuron (66).
POST	CONV	POST: bentazon + acifluorfen (29); sethoxydim (1/2; 53); bentazon + acifluorfen (NI; 56); 2,4-DB + linuron (66).
PRE + POST	GR	PRE: metribuzin + chlorimuron (H 4998); imazaquin (H 5545). POST: glyphosate (60).
POST	GR	POST: glyphosate (29); glyphosate (60).
		1998
PRE + POST	CONV	PRE: metribuzin + chlorimuron. POST: sethoxydim (1/4; 55); bentazon + acifluorfen (IRR; 64); 2,4-DB + linuron (NI; 72).
POST	CONV	POST: bentazon + acifluorfen (32); sethoxydim (1/2; 55); 2,4-DB + linuron (72).
PRE + POST	GR	PRE: metribuzin + chlorimuron. POST: glyphosate (72).
POST	GR	POST: glyphosate (32); glyphosate (72).
		1999
PRE + POST	CONV	PRE: metribuzin + chlorimuron. POST: 2,4-DB + linuron (39).
POST	CONV	POST: bentazon + acifluorfen + sethoxydim (22); 2,4-DB + linuron (36).
PRE + POST	GR	PRE: metribuzin + chlorimuron. POST: glyphosate (35).
POST	GR	POST: glyphosate (21); glyphosate (35).

† WMS, weed management system: PRE + POST = PRE broadleaf plus POST broadleaf and grass weed management and POST = POST broadleaf and grass weed management.
‡ + indicates either a premix or a tank mix. Rates are given in text. Values in parentheses are no. of days after planting applied.
§ 1/2 or 1/4 indicates a partial application; i.e., only areas containing grass were sprayed (classified as spot-sprayed).

after soybean leaf senescence (just before harvest) to measure the effect of the WMSs. Total cover was calculated as the sum of visually estimated values of weed cover by species that were obtained from five randomly chosen 0.5-m^2 sample areas in each plot. Estimates of weed cover in 10% increments from 0 to 100% were made to estimate cover for each weed species. If a species was present in any of the samples of an individual plot, then its relative abundance was categorized as at least 0 to 10% (average of 5% cover) in that sample. This is similar to the process used by Yelverton and Coble (1991) to measure weed resurgence at the end of the growing season following early-season application of WMSs intended to give 100% control.

Just before harvest each year, mature soybean plant height (length from the soil surface to the tip of stem) was measured in all plots. Lodging ratings were recorded each year using a scale of 1 (almost all plants erect) to 5 (all plants down). A field combine modified for small plots was used to harvest the four center rows of each plot. Seed from all plots were cleaned by the harvesting machine; thus, correction for foreign-matter content in seed of any treatment combination was not necessary in any year. Harvested seed were weighed and adjusted to 130 g moisture kg^{-1} seed.

Estimates of total costs and returns were developed for each annual cycle of each experimental unit using the Mississippi State Budget Generator (Spurlock and Laughlin, 1992). Total specified expenses were calculated using actual inputs for each treatment in each year of the experiment and included all direct and fixed costs but excluded costs for land, management, and general farm overhead, which were assumed to be the same for all treatment combinations. Direct expenses included costs for seed and seed fungicide, herbicides, roll-out vinyl pipe used in irrigation, labor, fuel, repair and maintenance of machinery and irrigation system, hauling harvested seed, and interest on operating capital. Fixed expenses were ownership costs for tractors, self-propelled harvesters, implements, sprayers, and the irrigation system.

Costs of variable inputs and machinery were based on prices paid by Mississippi farmers each year. Irrigation costs were based on a 65-ha furrow irrigation setup and included an annualized cost for the engine, well, pump, gearhead, generator, fuel tank and lines, and land leveling. Total fixed costs of the irrigation system consisted of annual depreciation, interest on investment, and insurance. Machinery ownership cost was estimated by computing the annual capital recovery charge for each machine and applying the per-hectare rate to each field operation. Insurance was estimated at 1% of the original investment. Within IRR and NI environments, expenses other than those for weed management for both cultivar types (CONV and GR) within a WMS and year were essentially the same.

Weed management costs after planting were calculated for each treatment and included charges for herbicides, surfactants, and application. All application costs included both vari-

Table 3. Average daily maximum air temperatures (max. T) and total rain amounts for indicated months during 1996 through 1999, and 30-yr normals at Stoneville, MS.

	1996		1997		1998		1999		30-yr normals†	
Month	Max. T	Rain	Max. T	Rain	Max. T	Rain	Max. T	Rain	Max. T	Rain
	°C	mm	°C	mm	°C	mm	°C	mm	°C	mm
Apr.	23.0	150	20.5	114	23.5	110	25.5	161	23.5	137
May	31.0	62	26.5	148	30.5	117	28.9	144	28.0	127
June	31.5	133	30.5	106	33.5	40	31.7	71	32.0	94
July	33.0	84	34.5	74	34.5	145	33.9	26	33.0	94
Aug.	31.5	110	31.5	71	34.5	18	35.6	6	32.5	58
Sept.	29.0	112	31.0	56	33.3	74	31.7	44	29.5	86

†1964–1993 (Boykin et al., 1995).

Table 4. After-planting weed management expense (WEXP) and total expense (TEXP) for nonirrigated and irrigated conventional (CONV) and glyphosate-resistant (GR) soybean cultivars grown under two levels of weed management (PRE + POST and POST) at Stoneville, MS, 1996–1999.

	Nonirrigated				Irrigated			
	PRE + POST†		POST‡		PRE + POST		POST	
Cultivar§	WEXP	TEXP	WEXP	TEXP	WEXP	TEXP	WEXP	TEXP
	$ ha^{-1}							
				1996				
CONV	145	320	108	281	145	403	108	366
GR	101	274	64	235	101	354	64	315
				1997				
CONV	164	349/339¶	144	327/317¶	125	454	105	432
GR	108/93#	292/280#	74	259	108/93#	444/428#	74	409
				1998				
CONV	112	358	102	347	110	458/475¶	102	462/476¶
GR	110	354	79	323	110	470	80	445
				1999				
CONV	95	333	102	340	95	495	102	502
GR	98	337	81	319	98	496	81	478
				Avg. across years				
CONV	129	340	114	322	119	457	104	445
GR	102	307	75	284	102	444	75	412

† PRE + POST = pre-emergent broadleaf followed by postemergent broadleaf and grass weed management.
‡ POST = postemergent weed management.
§ Extra seed cost shown in Table 1 for GR cultivars added to their weed management expense.
¶ First and second numbers for MG IV and MG V cultivars, respectively. Differences result from differences in seed cost, number of irrigations, or both.
# Different cost associated with use of metribuzin + chlorimuron premix with H 4998 (first number) vs. imazaquin with H 5545.

able and fixed expenses associated with tractors and sprayers. Weed management expenses for GR cultivars shown in Table 4 include the additional cost for their seed, which was \$0.22 kg^{-1} in 1996, \$0.49 kg^{-1} in 1997, \$0.44 kg^{-1} in 1998, and \$0.47 kg^{-1} in 1999.

Income from each experimental unit was calculated using the Mississippi market-year average price of \$0.253 kg^{-1} for both cultivars in 1996, \$0.279 kg^{-1} for 'D 478' and \$0.253 kg^{-1} for all other cultivars in 1997, and \$0.207 kg^{-1} for all cultivars in 1998. In 1997, a bonus was paid for early delivery of early maturing cultivars; therefore, this bonus resulted in the MG IV CONV cultivar receiving a higher price in 1997. The USDA loan price of \$0.196 kg^{-1} for Mississippi was used for 1999 calculations of income. Yearly prices were used to reflect the effect of market forces on income for each individual year. Use of annual prices is appropriate for ex post facto research where attempts are made to determine the cause or reason for differences that occur (Gay, 1987). In this case, it was deemed important to determine yearly fluctuations in net return as affected by differing costs, yields, and prices over the experimental period. Net return above total specified expenses was determined for each experimental unit each year.

Analysis of variance [PROC MIXED (SAS Inst., 1996)] was used to evaluate the significance of treatment effects on weed cover, plant height, seed yield, and net returns within the separate IRR and NI experiments. Analyses across years were not conducted because of the different cultivars in the different years. Analyses for individual years treated cultivar and WMS as fixed effects. Mean separation was achieved with an $LSD_{0.05}$.

RESULTS AND DISCUSSION

Weather and Soybean Development

Thirty-year average monthly maximum air temperatures and total rainfall (Boykin et al., 1995) at Stoneville are presented in Table 3. These normal weather patterns are associated with low yields from NI plantings because they result in drought stress to soybean that normally is in reproductive development from late June through early August (Heatherly, 1999c).

In 1996, average maximum air temperatures generally were near normal, and June through August rain was at or above normal (Table 3). Ninety-five percent of the June rain fell before the 20th while two-thirds of the July rain fell after the 28th. This period of low rainfall coincided with the beginning pod through mid-seed-fill periods of the two cultivars. In 1997, average maximum air temperatures were near or below normal during all months of the growing season. Rain during the April through August period was near normal. In 1998, monthly average maximum air temperatures were at or above normal during the April through August period. Rain amounts were below average in June and August. The shortage of rain in June was exacerbated by the fact that 95% of the May rain fell on 29 May. All of the above-normal (145 mm) rain in July occurred before 15 July while rain for the remainder of July and all of August totaled only 18 mm. The beginning-pod through full-seed periods for the MG V cultivars coincided with this lengthy period of low rainfall. In 1999, high temperatures in conjunction with low rainfall in July and August resulted in severe stress for all cultivars. This stress was exacerbated by the relatively late planting date of 17 May in 1999.

Weed Management Expense

Weed management cost for GR cultivars was always less with POST than with PRE + POST in both NI and IRR environments (Table 4). This agrees with findings of Webster et al. (1999), Reddy and Whiting (2000),

Table 5. Plant height for nonirrigated and irrigated conventional (CONV) and glyphosate-resistant (GR) soybean cultivars grown under two levels of weed management (PRE + POST and POST) at Stoneville, MS, 1996–2000.

Cultivar	Nonirrigated			Irrigated		
	PRE + POST†	POST‡	Avg.	PRE + POST	POST	Avg.
	cm					
1996						
DP 3478 (CONV)	64	68	66	67	69	68
A 4701 (GR)	65	64	65	70	71	71
Avg.	65	66		68	70	
$LSD_{0.05}$§	C = NS¶; W = NS; C × W = NS			C = NS; W = NS; C × W = NS		
1997						
D 478 (CONV)	52	50	51	56	60	58
H 4998 (GR)	86	85	86	120	120	120
Hutcheson (CONV)	43	42	42	46	49	48
H 5545 (GR)	52	53	52	70	62	66
Avg.	58	57		73	73	
$LSD_{0.05}$	C = 7; W = NS; C × W = NS			C = 6; W = NS; C × W = 6/5#		
1998						
D 478 (CONV)	56	58	57	36	54	45
H 4994 (GR)	42	52	47	32	52	42
P 9511 (CONV)	68	68	68	74	72	73
DP 5806 (GR)	50	58	54	46	56	51
Avg.	54	59		47	58	
$LSD_{0.05}$	C = 5; W = 3; C × W = NS			C = 8; W = 5; C × W = 11/7#		
1999						
AP 4880 (CONV)	98	100	99	104	104	104
P 9492 (GR)	79	84	82	88	91	90
P 9594 (CONV)	72	72	72	72	77	74
DP 5644 (GR)	78	84	81	66	83	75
Avg.	82	85		82	89	
$LSD_{0.05}$	C = 4; W = 2; C × W = NS			C = 5; W = 3; C × W = 7/7#		

† PRE + POST = pre-emergent broadleaf followed by postemergent broadleaf and grass weed management.
‡ POST = postemergent weed management.
§ C = LSD for cultivar mean separation; W = LSD for weed management system (WMS) separation; C × W = LSD(s) for cultivar × WMS interaction.
¶ NS = no significant difference.
# First number for comparing cultivar values within WMS; second number for comparing WMS values within cultivar.

and Reddy (2001a). Cost of POST for CONV cultivars was less than that for PRE + POST except in 1999. The 4-yr average cost for PRE + POST was \$102 ha^{-1} for GR cultivars in both NI and IRR treatments and \$119 and \$129 ha^{-1} for CONV cultivars in IRR and NI treatments, respectively. These differences are larger than those calculated by Webster et al. (1999). Our 4-yr average cost for POST was \$75 ha^{-1} for GR cultivars in both NI and IRR environments and \$104 and \$114 ha^{-1} for CONV cultivars in IRR and NI environments, respectively. This cheaper POST weed management with glyphosate vs. nonglyphosate POST herbicides agrees with results of Nelson and Renner (1999). Over the 4 yr of our study, POST for GR cultivars cost the least (\$75 ha^{-1}), and PRE + POST for CONV cultivars cost the most [\$119 (IRR) and \$129 (NI) ha^{-1}]. Differences in total expenses (excluding charges for land, management, and general farm overhead) followed the same pattern as the differences in weed management expenses (Table 4).

Plant Height and Lodging

Lodging of all cultivars in the NI environment and in the 1996 and 1998 IRR environment was rated 1.0 (almost all plants erect; data not shown). In the 1997 IRR environment, 'H 4998' (GR) was rated 4.0 (either all plants leaning considerably or >50% of plants down) while all other cultivars were rated as 1.0. In the 1999 IRR environment, 'AP 4880' (CONV) was rated as 2.0 (all plants leaning slightly) while all other cultivars were rated as 1.0.

In the 1996 and 1997 studies, WMS did not affect plant height (Table 5). In the 1998 and 1999 NI environments, the POST WMS resulted in plants that averaged 5 and 3 cm taller, respectively. In 1998 and 1999 IRR environments, the cultivar × WMS interaction affected height. With some cultivars, POST resulted in plants that were taller than those in PRE + POST while with other cultivars, there was no difference in height between PRE + POST and POST. The lodging of H 4998 (GR) in the 1997 IRR environments was likely related to its height of 120 cm.

Weed Cover

As stated earlier, the intent of this study was to use proven weed management options that differ in cost to achieve acceptable weed control for both CONV and GR cultivars. The two WMSs (PRE + POST vs. POST) accomplished this.

Nonirrigated

Neither WMS nor cultivar consistently affected weed cover. In 1996, weed cover at soybean maturity was greater in POST (19%) than in PRE + POST (14%) while in succeeding years, WMS did not affect weed cover (Table 6). In 1996, the GR cultivar had greater weed cover than the CONV cultivar while in 1998,

Table 6. Weed cover at harvest in conventional (CONV) and glyphosate-resistant (GR) soybean grown with two weed management systems (PRE + POST and POST) in nonirrigated and irrigated environments at Stoneville, MS, 1996–1999.

	Nonirrigated			Irrigated		
Cultivar	PRE + POST†	POST‡	Avg.	PRE + POST	POST	Avg.
			%			
			1996			
DP 3478 (CONV)	12	16	14 b§	22	18	20 b
A 4701 (GR)	16	22	19 a	28	28	28 a
Avg.	14 b	19 a		25 a	23 a	
			1997			
D 478 (CONV)	11	18	15 a	21	20	20 a
H 4998 (GR)	11	13	12 a	1	2	2 c
Hutcheson (CONV)	14	11	12 a	9	13	11 b
H 5545 (GR)	10	10	10 a	2	2	2 c
Avg.	11 a	13 a		8 a	9 a	
			1998			
D 478 (CONV)	2	10	6 a	79	38	58 a
H 4994 (GR)	0	1	1 b	71	8	40 bc
P 9511 (CONV)	4	11	8 a	59	2	30 c
DP 5806 (GR)	2	0	1 b	57	33	45 ab
Avg.	2 a	5 a		67 a	20 b	
			1999			
AP 4880 (CONV)	3	0	2 a	4	13	8 a
P 9492 (GR)	0	0	0 a	2	1	1 b
P 9594 (CONV)	6	1	3 a	3	5	4 ab
DP 5644 (GR)	0	0	0 a	6	4	5 ab
Avg.	2 a	0 a		4 a	6 a	

† PRE + POST = pre-emergent broadleaf followed by postemergent broadleaf and grass weed management.
‡ POST = postemergent weed management.
§ Within year and irrigation environment, numbers within a column (cultivar means) or within a row (weed management system means) followed by different letters are significantly different at $P \leq 0.05$.

CONV cultivars had the greater weed cover. In 1997 and 1999, weed cover was not affected by cultivar.

The relatively high weed covers at soybean maturity in 1996 and 1997 probably resulted from the August rain of 110 mm (1996) and 71 mm (1997) that occurred (Table 3) when canopies of the MG IV cultivars were opening due to leaf senescence. This becomes apparent when compared with the lower weed cover values at soybean maturity in 1998 and 1999 when August rain was 18 and 6 mm, respectively. Species with a major presence in 1996 were barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], browntop millet [*Brachiaria ramosa* (L) Stapf], pitted morningglory (*Ipomoea lacunosa* L.), prickly sida (*Sida spinosa* L.), and johnsongrass [*Sorghum halepense* (L.) Pers.]. In 1997, majority species were pitted morningglory, prickly sida, and red sprangletop [*Leptochloa filiformis* (L.) Beauv.].

Irrigated

Weed cover was affected by WMS only in 1998 when PRE + POST had 67% cover and POST had 20% cover (Table 6). Weed cover was relatively high in 1996 and 1998, and major weed species both years were barnyardgrass, browntop millet, ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq.], and pitted morningglory.

The extremely high weed cover at soybean maturity in PRE + POST in 1998 was an anomaly. It was associated with short plants and incomplete or uneven canopy closure [except 'P 9511' (CONV)] and consisted mostly of browntop millet, which did not interfere with harvest efficiency. As stated earlier, weed control before irrigation was excellent in both WMSs. Thus, high weed cover measured at soybean maturity in PRE + POST in 1998 was the result of late-season weed infestations developing through an incomplete crop canopy formed by short plants and enhanced by well-watered soil from irrigation during reproductive development.

Weed cover values were different among cultivars each year, but there was not a consistent trend across years (Table 6). In 1996 and 1997, CONV cultivars had the higher cover values while in 1998 and 1999, both CONV and GR cultivars had the higher values.

Seed Yield and Net Return

Nonirrigated

In 1996, neither cultivar nor WMS affected yield; however, average net return was higher from the GR cultivar (Table 7). This resulted from the lower estimated weed management cost for the GR cultivar (Table 4). There was no difference in net return between PRE + POST and POST. In 1997, use of GR cultivars within each MG resulted in greater average yield and net return. The higher net return resulted from both lower weed management cost and greater yield for the GR cultivars.

In 1998, cultivar affected both yield and net return (Table 7). The MG IV cultivars achieved both greater yield and net return than the MG V cultivars. There were no differences in yield and net return between CONV and GR cultivars. The difference in average yield between PRE + POST and POST was small and not significant, but the small yield advantage for POST combined with its lower weed management cost (Table 4) resulted in higher average net return from POST. In 1999, the MG IV GR cultivar produced the highest average yield and net return while there were

Table 7. Seed yield and net returns for nonirrigated conventional (CONV) and glyphosate-resistant (GR) soybean cultivars grown under two levels of weed management (PRE + POST and POST) at Stoneville, MS, 1996–1999.

Cultivar	Yield			Net return		
	PRE + POST†	POST‡	Avg.	PRE + POST	POST	Avg.
	kg ha^{-1}			\$ ha^{-1}		
			1996			
DP 3478 (CONV)	1680	1695	1690	133	176	155
A 4701 (GR)	1685	1610	1650	181	199	190
Avg.	1685	1650		157	188	
$LSD_{0.05}$§	C = NS¶; W = NS; C × W = NS			C = 35; W = NS; C × W = NS		
			1997			
D 478 (CONV)	1210	1185	1200	−11	3	−4
H 4998 (GR)	1560	1605	1585	103	151	127
Hutcheson (CONV)	1650	1495	1570	79	62	70
H 5545 (GR)	2145	2185	2165	263	294	278
Avg.	1640	1620		109	127	
$LSD_{0.05}$	C = 195; W = NS; C × W = NS			C = 48; W = NS; C × W = NS		
			1998			
D 478 (CONV)	2190	2115	2155	127	122	124
H 4994 (GR)	2155	2410	2280	125	213	169
P 9511 (CONV)	1730	1790	1760	28	52	40
DP 5806 (GR)	1475	1665	1570	−26	47	10
Avg.	1885	1995		63	108	
$LSD_{0.05}$	C = 250; W = NS; C × W = NS			C = 54; W = 34; C × W = NS		
			1999			
AP 4880 (CONV)	760	845	805	−183	−175	−179
P 9492 (GR)	1240	1225	1235	−94	−79	−87
P 9594 (CONV)	895	915	905	−157	−160	−158
DP 5644 (GR)	700	750	725	−198	−171	−185
Avg.	900	935		−158	−146	
$LSD_{0.05}$	C = 225; W = NS; C × W = NS			C = 43; W = NS; C × W = NS		
			1997–1999 avg.			
MG# IV (CONV)	1390	1380		−17	−17	
MG IV (GR)	1650	1745		45	95	
MG V (CONV)	1425	1400		−17	−15	
MG V (GR)	1440	1535		13	57	

† PRE + POST = pre-emergent broadleaf followed by postemergent broadleaf and grass weed management.
‡ POST = postemergent weed management.
§C = LSD for cultivar mean separation; W = LSD for weed management system (WMS) separation; C × W = LSD(s) for cultivar × WMS interaction.
¶ NS = no significant difference.
# MG, maturity group.

no differences in average yields and net returns between PRE + POST and POST. Low yields in 1999 caused by extreme drought resulted in negative net returns in all cases.

Over the 1997–1999 period, average yield of GR cultivars within MG was numerically higher than that of CONV cultivars within MG. This higher yield coupled with lower weed management costs for GR cultivars resulted in their average net returns being greater than those of CONV cultivars within MG. Differences in yield between PRE + POST and POST were small across the 3 yr at this location. However, the across-year average net returns were greater for GR cultivars in POST than in PRE + POST (\$95 vs. \$45 ha^{-1} and \$57 vs. \$13 ha^{-1}). This agrees with results of Culpepper et al. (2000) and Reddy (2001a).

Irrigated

In 1996, cultivar and WMS interacted to affect both yield and net return (Table 8). 'DP 3478' (CONV) with POST produced the highest yield, and this combined with its lower weed management cost (Table 4) resulted in the greatest net return. There were no differences between PRE + POST and POST yields and net returns for the GR cultivar. In 1997, use of the CONV cultivar within each MG resulted in greater average yield. The higher price received for D 478 (CONV) harvested seed plus its slightly higher yield resulted in greatest net return. The slightly higher average yield from POST plus its lower weed management cost (Table 4) resulted in its average net return being greater than that from PRE + POST.

In 1998, the cultivar × WMS interaction affected (magnitude) both yield and net return (Table 8). With all cultivars, POST resulted in the greater yield and net return. Within WMS, P 9511 produced a higher yield and net return than 'DP 5806'. The low yield from all cultivars treated PRE + POST was unexpected, and the reasons were not obvious. The low yields in PRE + POST were associated with extremely high weed cover values in this WMS at soybean maturity (Table 6).

In 1999, cultivar affected yield and net return (Table 8). The CONV cultivars produced a higher yield than their GR counterparts within each MG. There was no difference in net returns between the CONV and GR cultivars in MG IV, but there was a difference between CONV and GR cultivars in MG V. There were no differences between PRE + POST and POST yields and between PRE + POST and POST net returns.

Over the 1997–1999 period, average yield of CONV

Table 8. Seed yield and net returns for irrigated conventional (CONV) and glyphosate-resistant (GR) soybean cultivars grown under two levels of weed management (PRE + POST and POST) at Stoneville, MS, 1996–1999.

Cultivar	Yield			Net return		
	PRE + POST†	POST‡	Avg.	PRE + POST	POST	Avg.
	kg ha^{-1}			$ ha^{-1}		
			1996			
DP 3478 (CONV)	3725	4080	3905	603	735	669
A 4701 (GR)	3320	3270	3295	541	567	554
Avg.	3525	3675		572	651	
LSD$_{0.05}$§	C = 195; W = 195; C × W = 275			C = 51; W = 51; C × W = 73		
			1997			
D 478 (CONV)	4075	4200	4140	680	737	708
H 4998 (GR)	3525	3800	3660	449	553	501
Hutcheson (CONV)	3920	3785	3850	542	530	536
H 5545 (GR)	3400	3470	3435	434	471	453
Avg.	3730	3815		526	573	
LSD$_{0.05}$	C = 365; W = NS¶; C × W = NS			C = 91; W = 46; C × W = NS		
			1998			
D 478 (CONV)	1810	3960	2885	−84	356	136
H 4994 (GR)	1590	3645	2615	−138	307	84
P 9511 (CONV)	2565	4240	3405	56	400	228
DP 5806 (GR)	1865	2535	2200	−87	80	−3
Avg.	1960	3595		−63	286	
LSD$_{0.05}$	C = 384; W = 270; C × W = 545			C = 77; W = 55; C × W = 109		
			1999			
AP 4880 (CONV)	4410	4190	4300	372	324	348
P 9492 (GR)	4045	4095	4070	301	329	315
P 9594 (CONV)	4195	4265	4230	329	335	332
DP 5644 (GR)	3650	3815	3735	221	270	246
Avg.	4075	4090		306	314	
LSD$_{0.05}$	C = 220; W = NS; C × W = NS			C = 42; W = NS; C × W = NS		
			1997–1999 avg.			
MG# IV (CONV)	3430	4115		323	472	
MG IV (GR)	3055	3845		204	396	
MG V (CONV)	3560	4095		309	422	
MG V (GR)	2970	3275		189	274	

† PRE + POST = pre-emergent broadleaf followed by postemergent broadleaf and grass weed management.
‡ POST = postemergent weed management.
§ C = LSD for cultivar mean separation; W = LSD for weed management system (WMS) separation; C ×W = LSD for cultivar × WMS interaction.
¶ NS = no significant difference.
# MG, maturity group.

cultivars within MG was higher than that of GR cultivars within MG. This higher yield resulted in greater average net returns from the CONV cultivars in spite of the higher costs for weed management in them. This agrees with the results from studies with IRR GR and IRR CONV cultivars in Arkansas (Webster et al., 1999).

Both yield and net return were considerably larger with POST than with PRE + POST across years in our study. In Arkansas, late May to early June plantings of an IRR GR cultivar produced similar yield and net return from PRE + POST and POST-only weed management in one study (Payne and Oliver, 2000) and similar yield but higher net return following POST-only weed management in another study (Webster et al., 1999).

SUMMARY AND CONCLUSIONS

Results from agronomic research rarely are devoid of effects of years or interactions between or among years and experimental variables. Thus, the following conclusions are based on results across years because producers must make decisions based on multiyear results, regardless of the presence or absence of interactions.

The use of GR cultivars grown in a NI or low-yield environment results in greater profit at sites represented by this location. This agrees with results from studies in North Carolina (Culpepper et al., 2000). In an IRR or high-yield environment, our results indicate that use of CONV vs. GR cultivars results in greater profit. This agrees with results from IRR studies in Arkansas (Webster et al., 1999) and Nebraska (Elmore et al., 2001b). Our results also indicate that use of PRE followed by POST weed management vs. using only POST weed management is not necessary for achieving highest yield or net return with either CONV or GR cultivars. This agrees with the findings of Gonzini et al. (1999), Nelson and Renner (1999), Roberts et al. (1999), Corrigan and Harvey (2000), and Payne and Oliver (2000).

These results are not to be construed to mean that use of PRE weed management is an unacceptable practice. In operations where timeliness of POST weed management is a logistical problem, PRE management can certainly be warranted. However, its use may not result in the greatest profit opportunity as indicated by the results from this study; in fact, profits may be reduced by inclusion of PRE weed management. Choice of GR vs. CONV cultivars should be based on (i) expected weed pressure in specific fields, (ii) cost of using GR cultivars and glyphosate vs. availability and cost of CONV cultivars and nonglyphosate herbicides, (iii) yield potential of GR vs. CONV cultivars, and (iv) yield potential of a particular production or management system (e.g., IRR vs. NI). The GR cultivars' genetics should be viewed as a weed management option rather than a selection criterion.

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